

(Noll: residual error - 7)

Exercise 2: Which mirror configuration for a (minimum, other errors excluded) goal Strehl ratio of 30% in band J ($1.25\mu\text{m}$) ?

[knowing that: $r_0@500\text{nm} = 12\text{cm}$ and $D = 8\text{m}$, and that nb of Z modes corrected = $(n+1)(n+2)/2$ piston included, n being the radial order]

-> For next session: solve this exercice !!
(IDL batch, and also function)

(Noll: residual error - 7+)

- Fried parameter in band J: $r_0[J] = 0.12 (1.25/0.5)^{6/5} \approx 0.36$
- What we want is hence (thanks to Maréchal and Noll):
$$0.3 \leq \exp\{-0.2944 J \sqrt{3}/2 (D/r_0)^{5/3}\}$$
Then: $J \geq (-\ln(.3)/.2944 (0.36/8)^{5/3})$, i.e.: $J \geq 76.8$
- But: $J = (N+1)(N+2)/2 \Rightarrow N = 11$ is necessary
 $\Rightarrow$ we need $N=11$ radial orders corrected (which corresponds to $J=78$ Zernike modes).
- This leads to a 11x11-subapertures WFS, and then a 12x12-actuators DM (considering Fried's configuration).

(Noll: residual error - 7++)

```
; call with: IDL> @Exo1
Diam  =8.0
r0    =0.12
Strehl=0.3
band  =1.25E-6

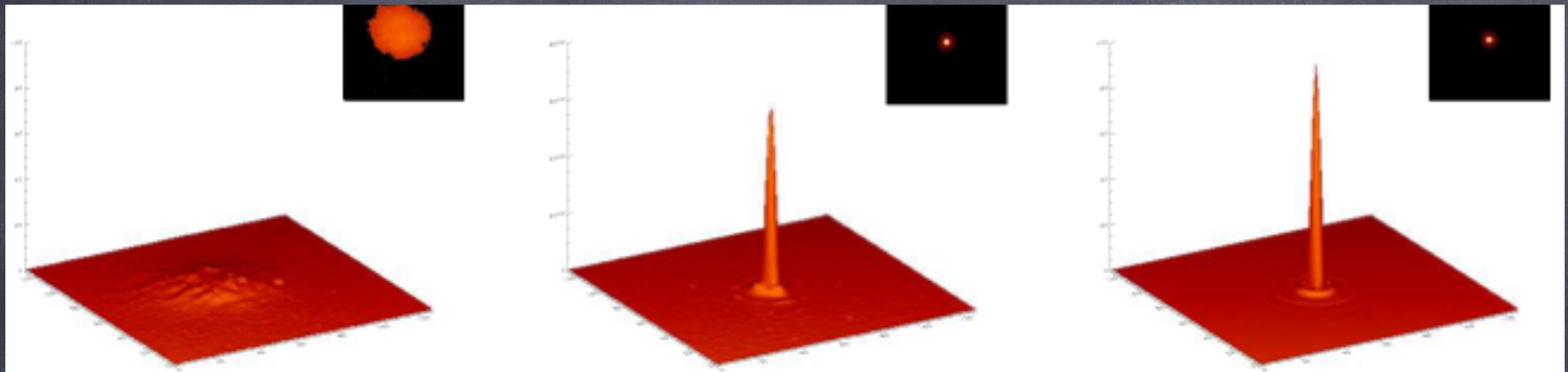
r0_band=r0*(band/500E-9)^(6./5)
J=(-.2944/alog(Strehl)*(Diam/r0_band)^(5./3))^(2./sqrt(3))
N=(-3+sqrt(*+8*J))/2          → 1+8J
if N ne floor(N) then N=floor(N)+1
; see result with: IDL> print, N
```

```
function Ncalc, Diam, r0, Strehl, band
; call with: IDL> N=Exo_function(Diam, r0, Strehl, band)

r0_band=r0*(band/500E-9)^(6./5)
J=(-.2944/alog(Strehl)*(Diam/r0_band)^(5./3))^(2./sqrt(3))
N=(-3+sqrt(*+8*J))/2          → 1+8J
if N ne floor(N) then N=floor(N)+1

return, N-1
end
```

Post-AO PSF morphology - 1



no correction

corrected ($SR = 64\%$)

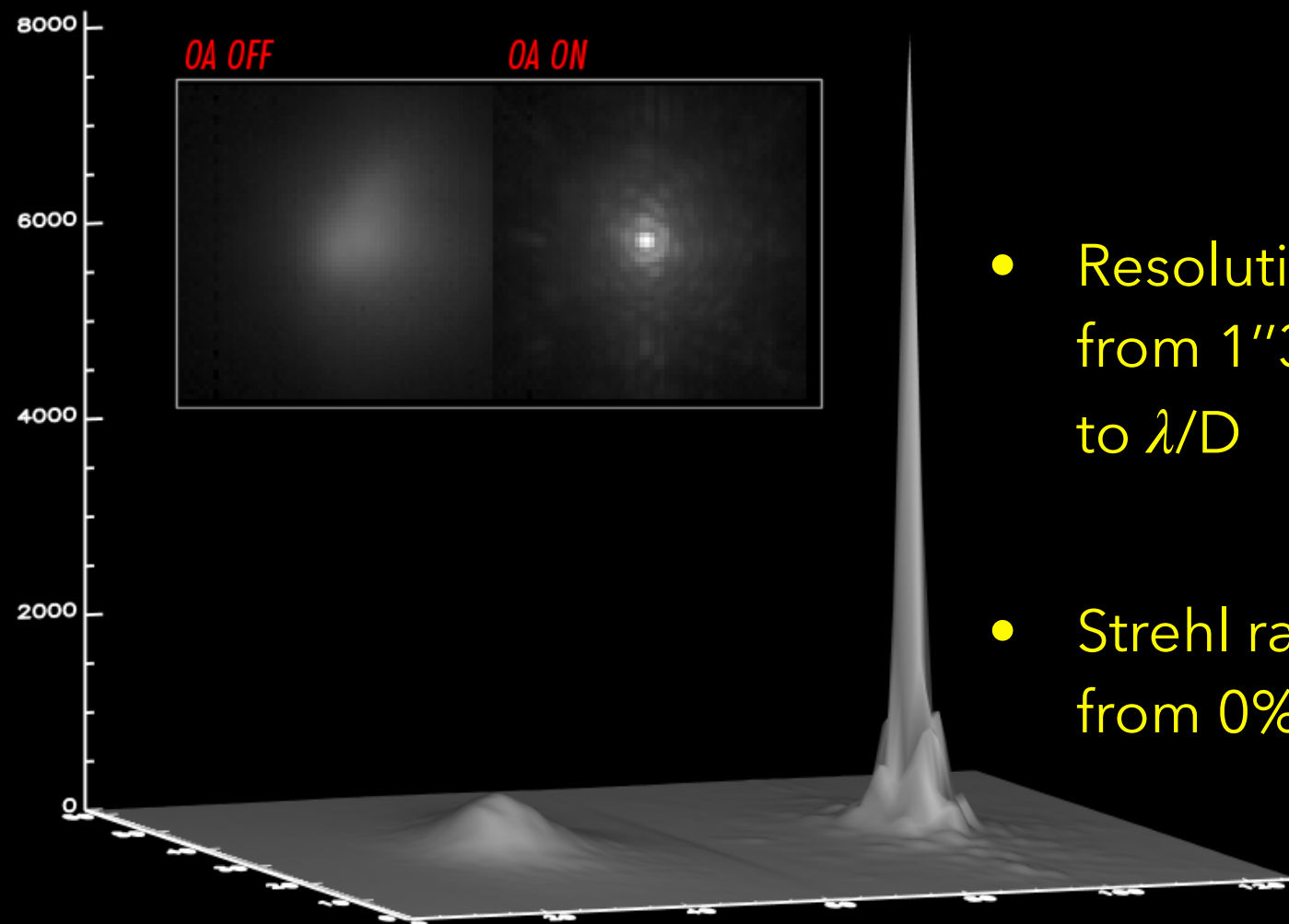
Airy pattern

Imaging wavelength : $2.2\mu m$

Turbulence : $r_o = 1m$ à $2.2\mu m$, wind speed = $10m/s$, telescope : $D = 8m$

System (NAOS) : 144 sub-aperture, 185 actuators, $500Hz$ temporal sampling frequency

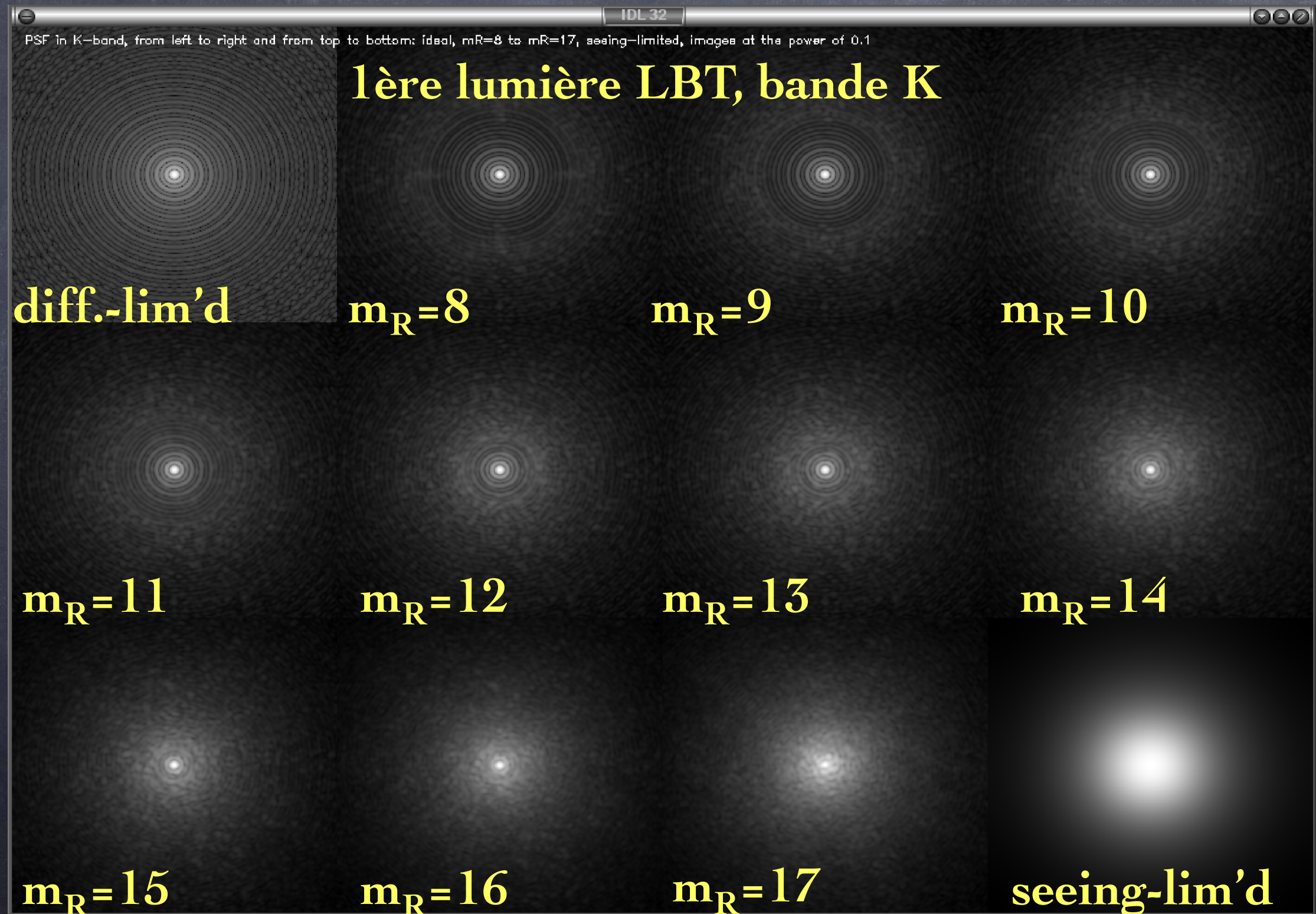
Post-AO PSF morphology - 1+



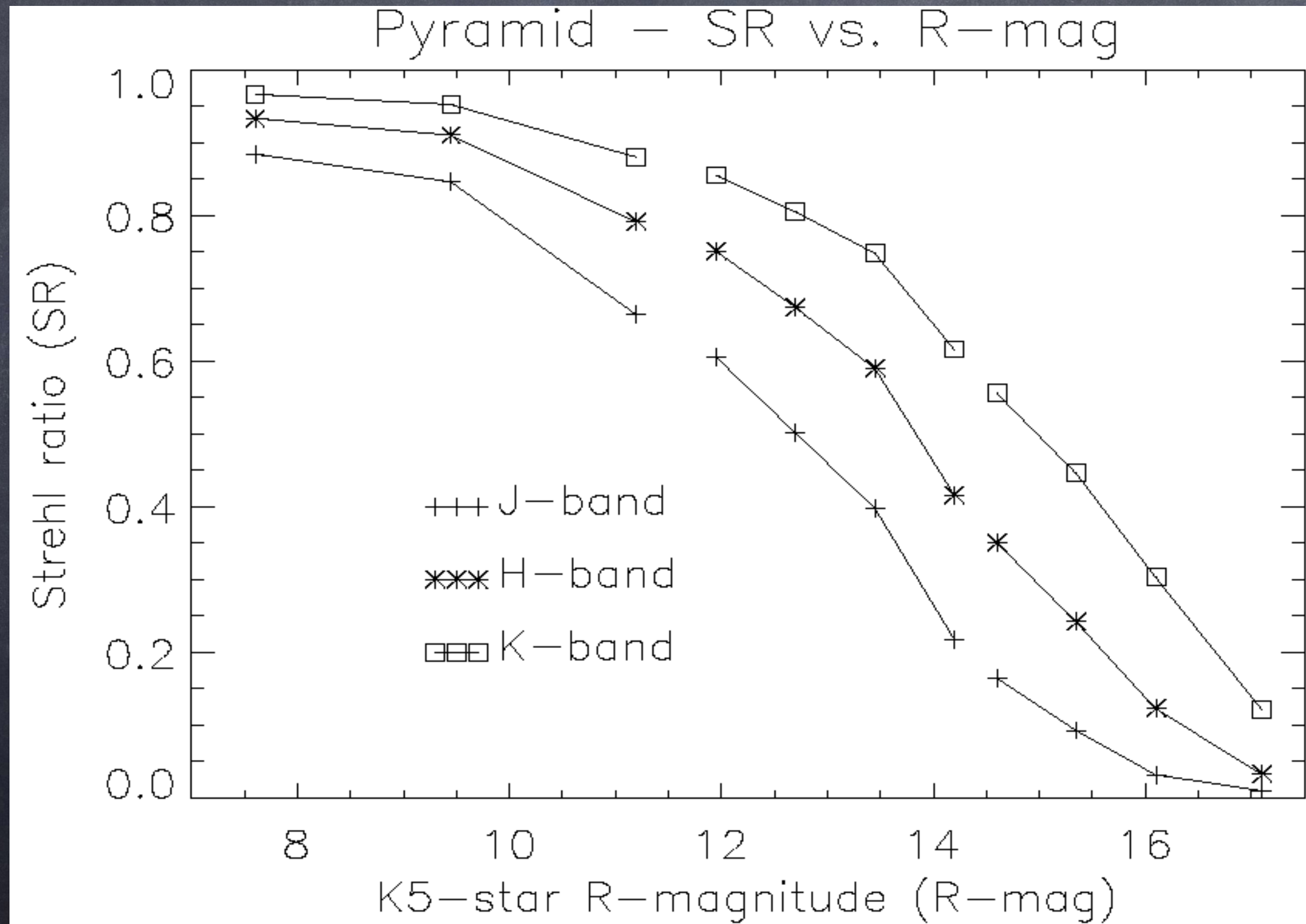
- Resolution: from $1''3$ to λ/D
- Strehl ratio (in H band): from 0% to 30+%

[AOC, March 5th 2025]

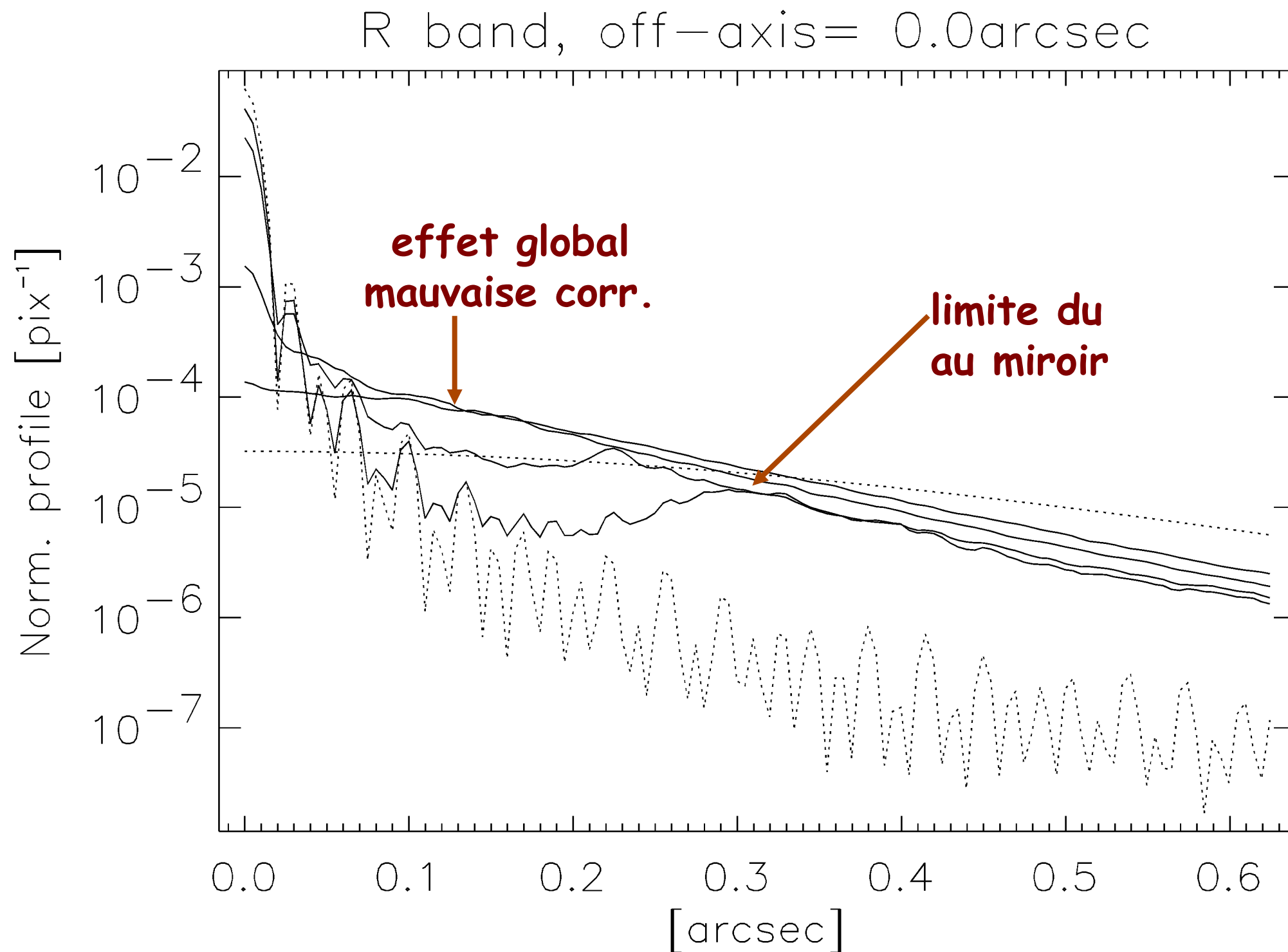
Post-AO PSF morphology - 2



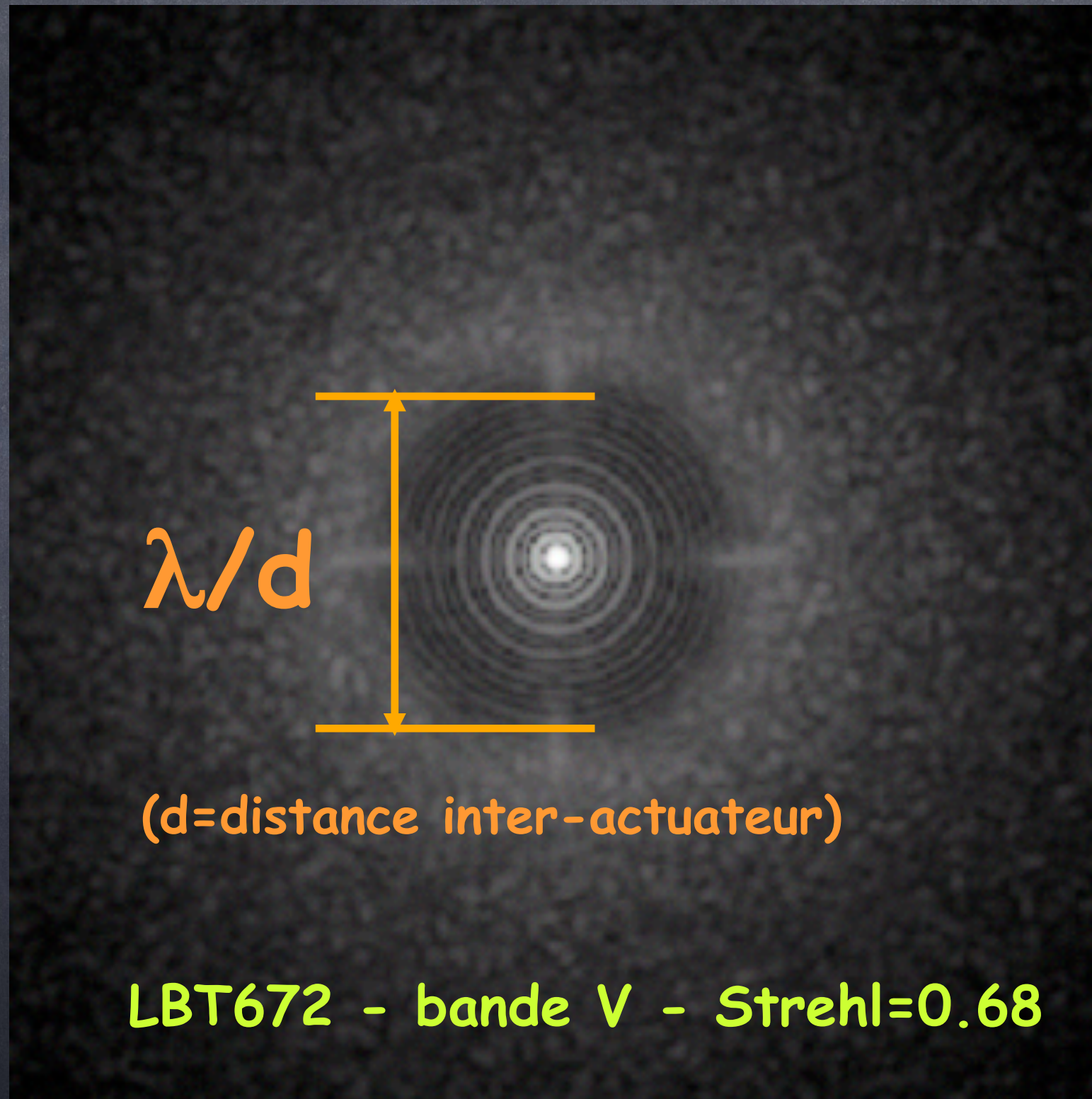
Post-AO PSF morphology - 3



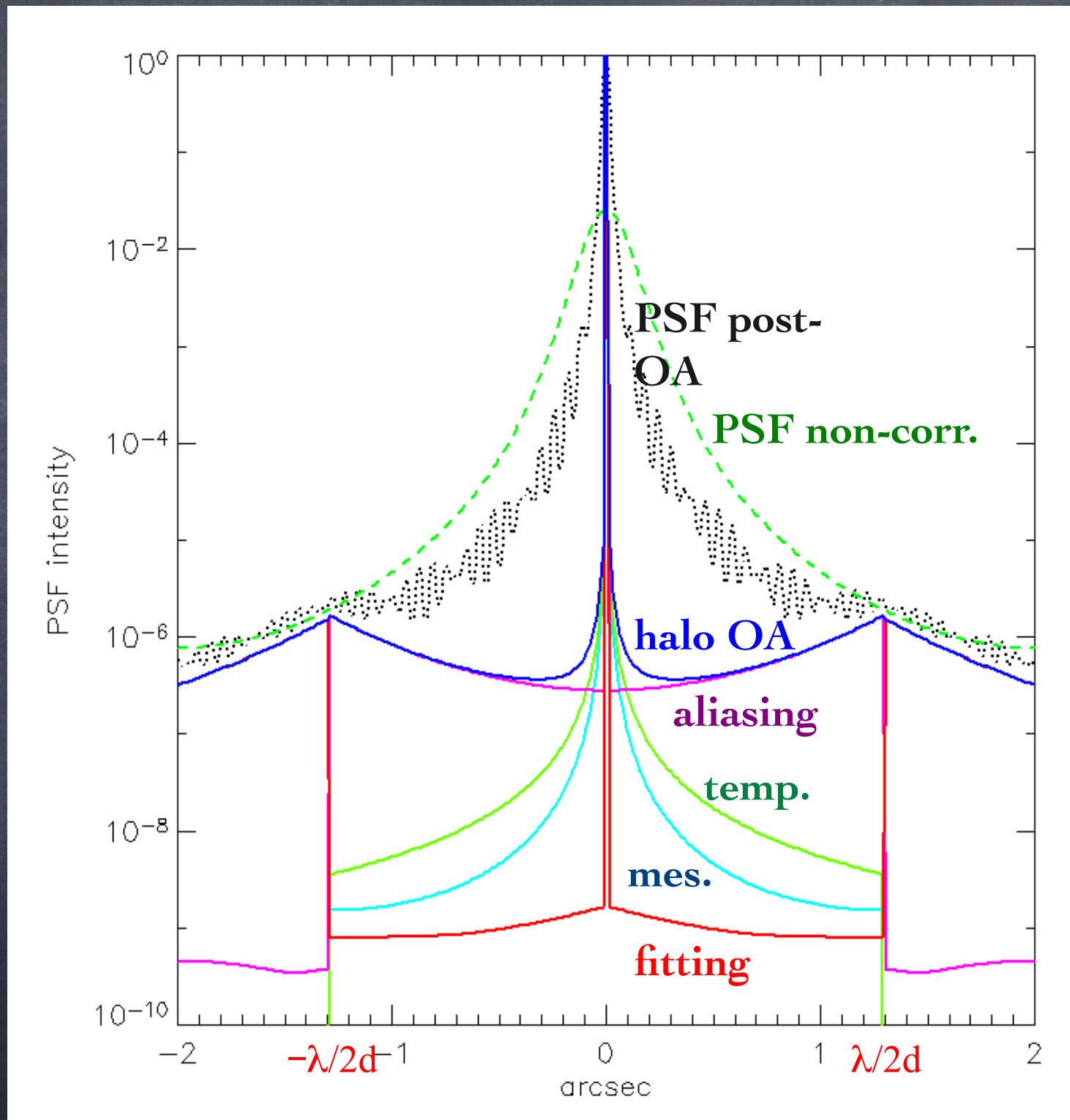
Post-AO PSF morphology - 4



Post-AO PSF morphology - 5



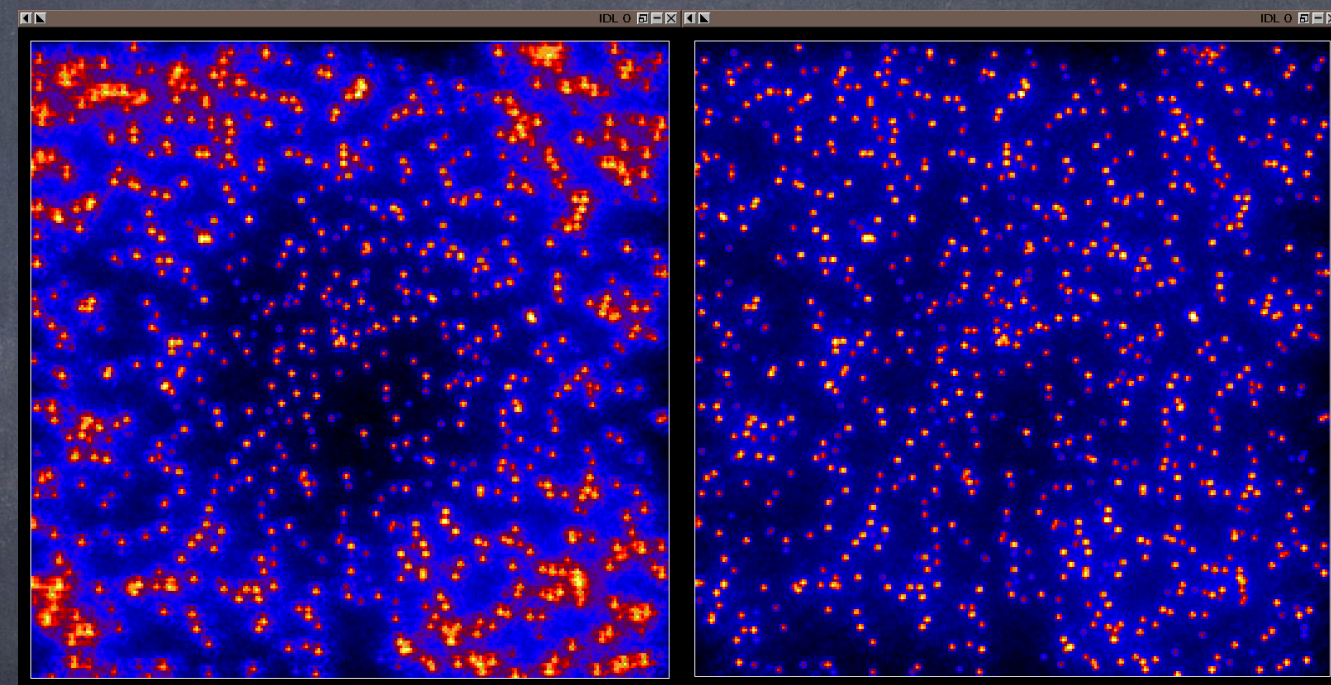
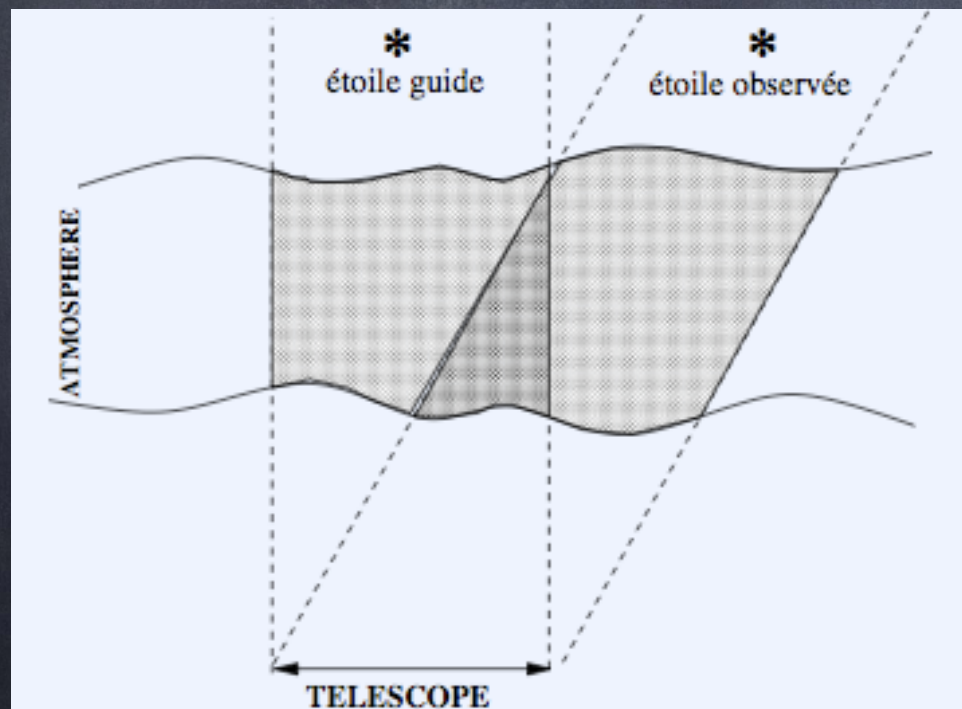
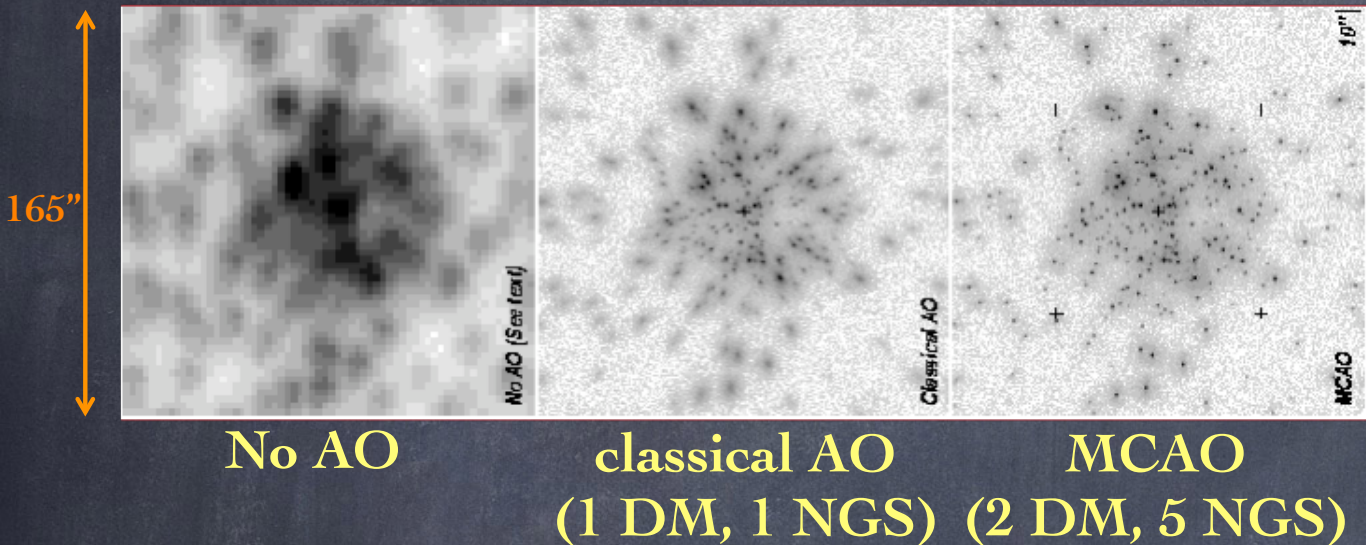
Post-AO PSF morphology - 6



See also Jolissaint et al. (JOSAA, 2006) and Jolissaint (JEOS, 2010), (and also Rigaut, Véran and Lai (SPIE 1998)).

Post-AO PSF morphology - 7

Wide-field AO case: anisoplanatism...



(bande J, champ de 1', simu. B.Ellerbroek, Gemini Obs.)



Wavefront sensors - 1

First example of wavefront sensor: Shack-Hartmann

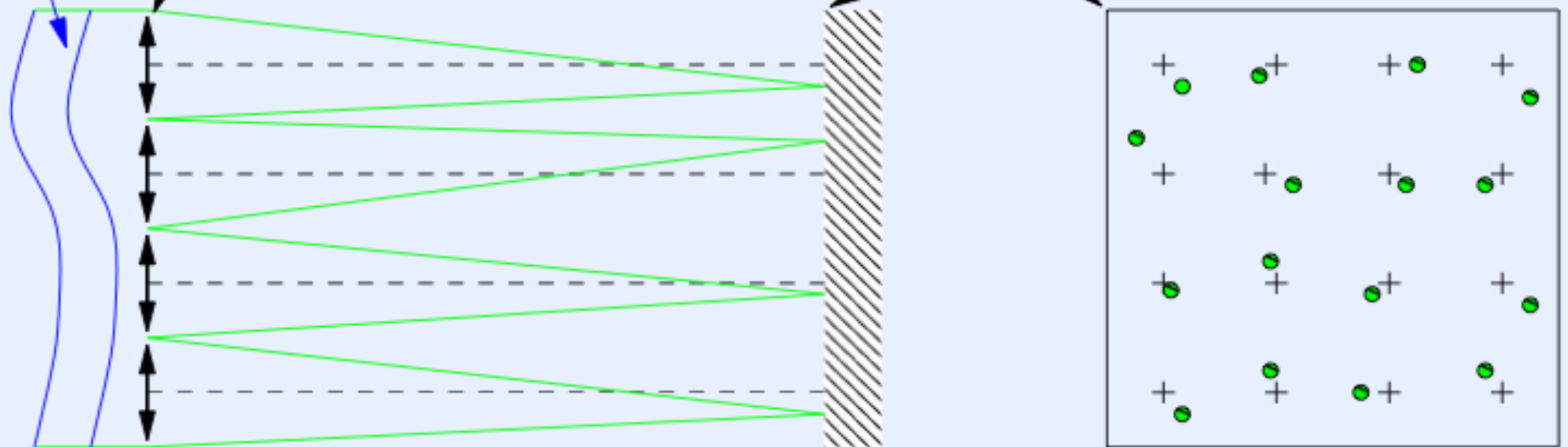
Front d'onde turbulent

Matrice de micro-lentilles

matrice CCD

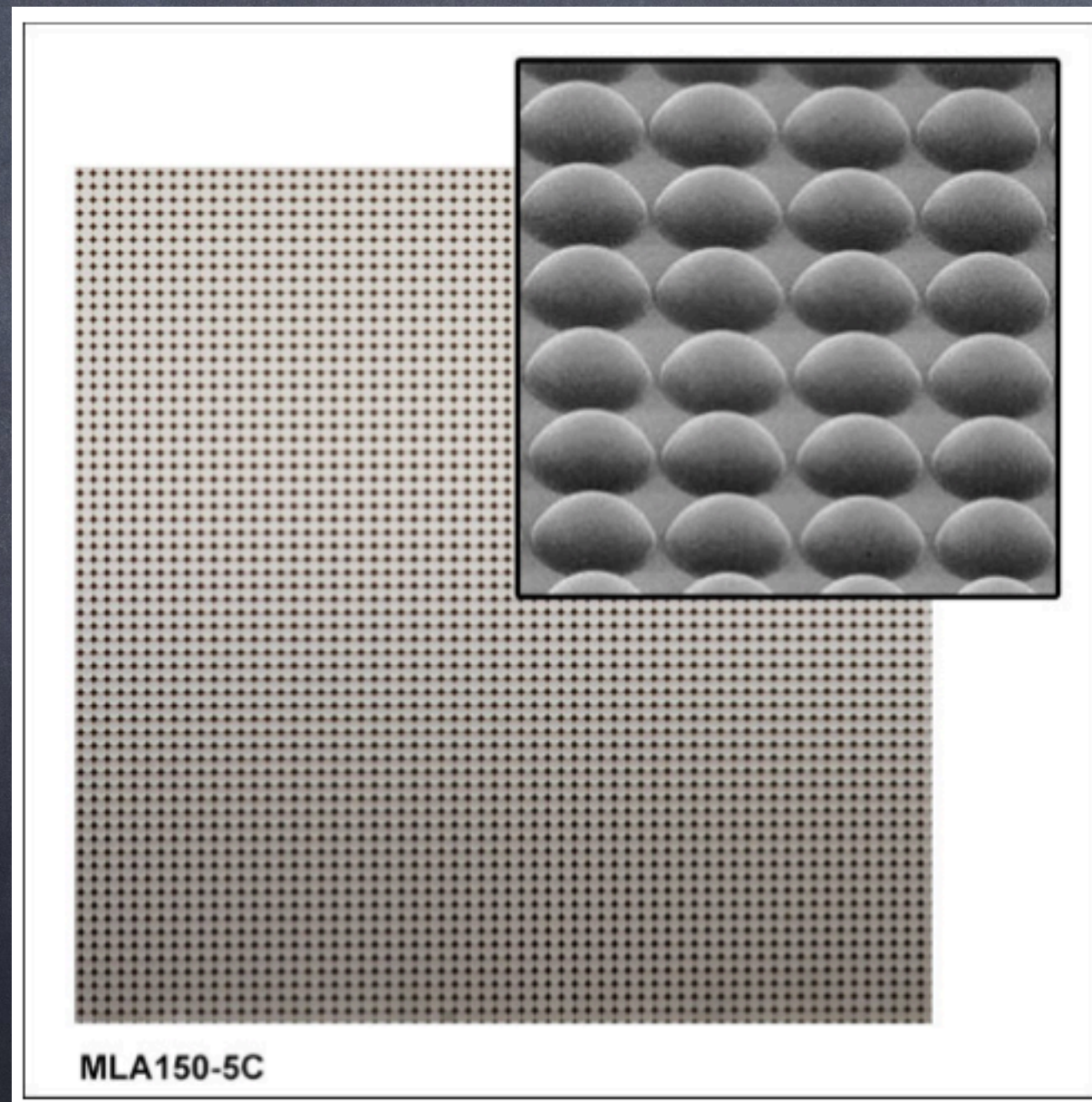
● spot turbulent

+ axe optique



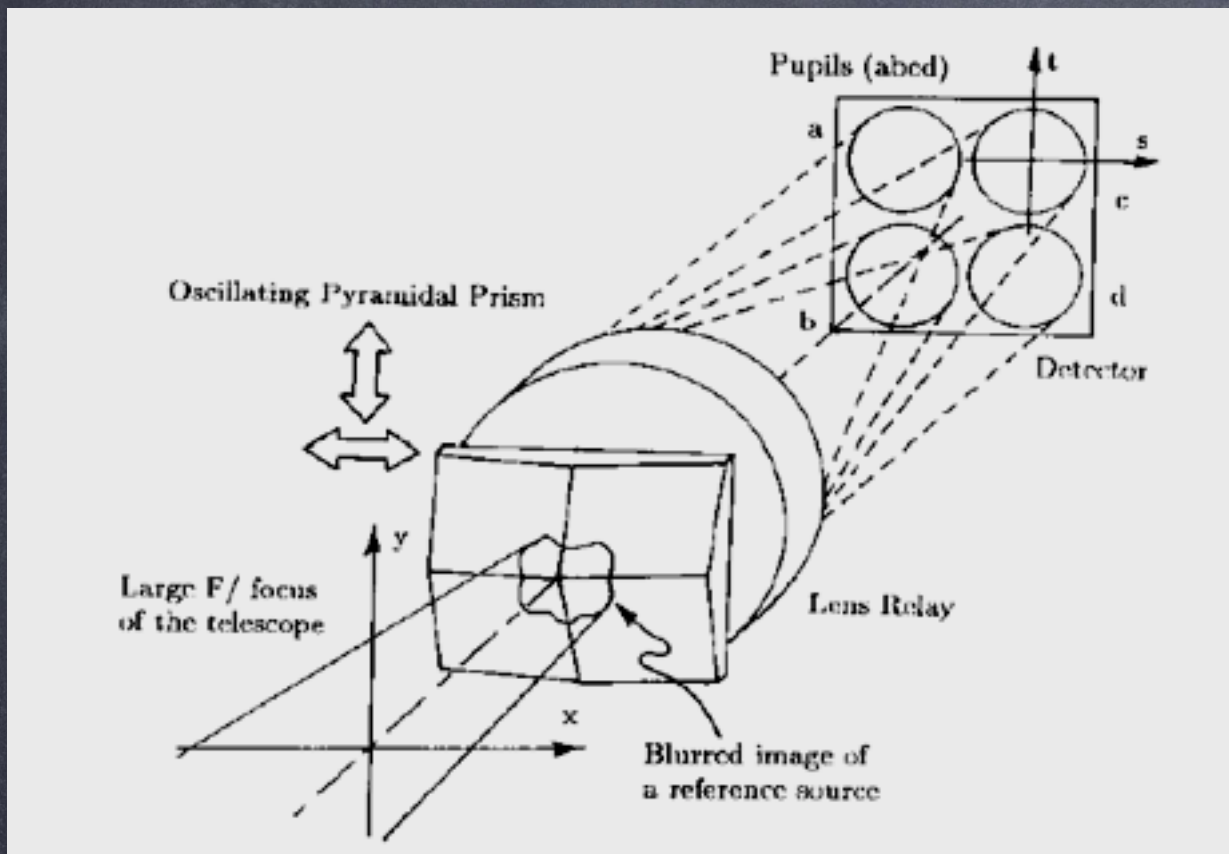
Wavefront sensors - 2

First example of wavefront sensor: Shack-Hartmann

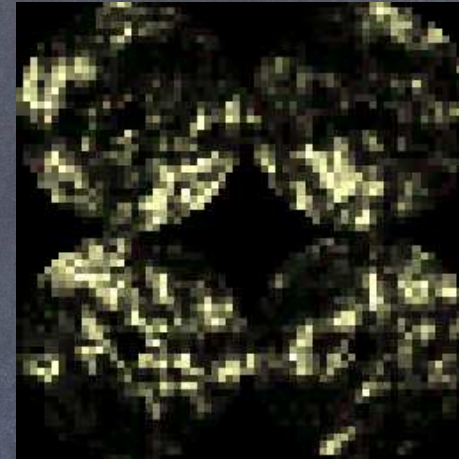


Wavefront sensors - 3

Another example: the Pyramid WFS



boucle ouverte

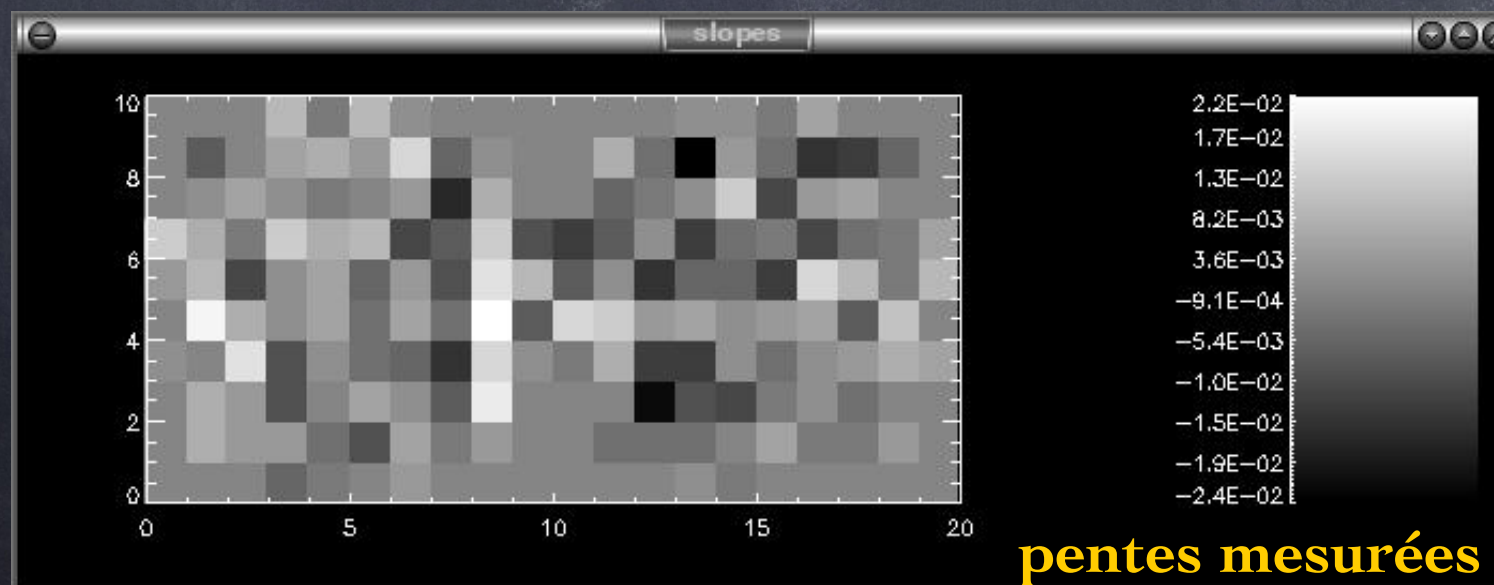


boucle fermée



$$S_x(x, y) = \frac{(I_1 + I_4) - (I_2 + I_3)}{\sum_i I_i}$$

$$S_y(x, y) = \frac{(I_1 + I_2) - (I_3 + I_4)}{\sum_i I_i}$$



pentes mesurées

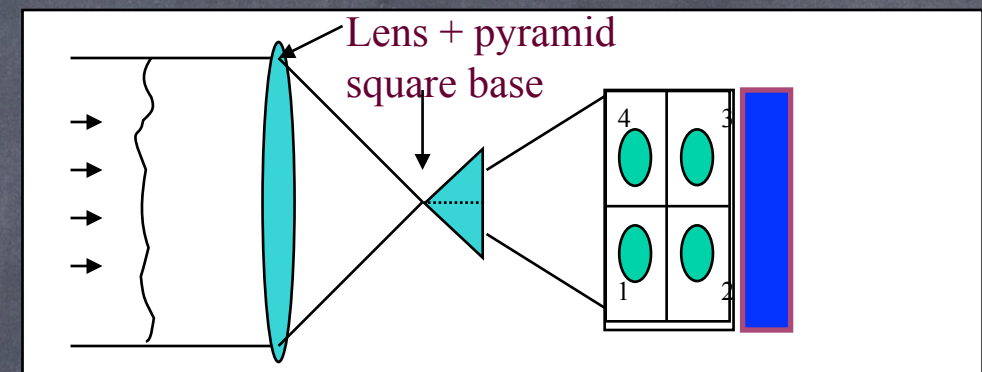
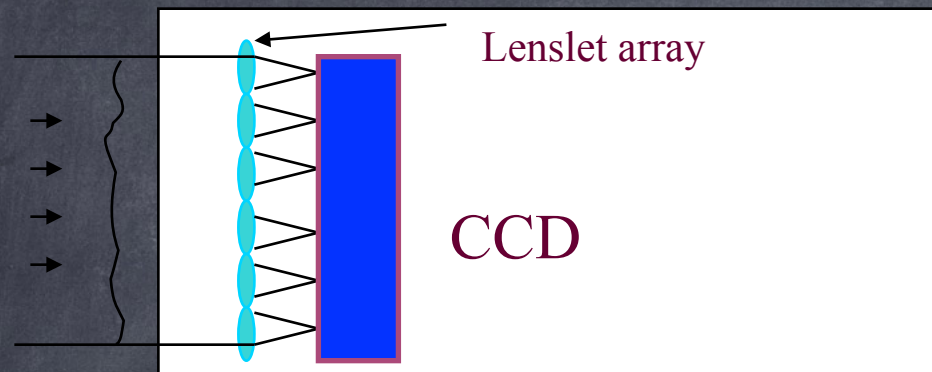
Wavefront sensors - 4

Another example: the Pyramid WFS



WH telescope's AO system

Wavefront sensors - 5



- SH: First on-sky AO results with COME-ON/VLT in 1989 [Rousset et al. 1990].
- Pyramid [Ragazzoni 1996], 2-*mag.* gain foreseen with respect to SH [Ragazzoni & Farinato 1999], confirmed by Monte-Carlo simulations [Esposito & Riccardi 2001].

Wavefront sensors - 6

Pyramid vs. Shack-Hartmann, 1st round

- Rousset et al., 1989-1990: 1st results of a SH WFS on sky on the VLT (COME-ON)
- Ragazzoni, 1996: proposal of a pyramid WFS
- Ragazzoni & Farinato, 1999: theoretical gain of 2 mag. (in limiting mag.)
- Esposito & Riccardi, 2001: gain confirmed by numerical simulations (but in open-loop and not the whole AO error budget)
- Carbillet et al., 2003: gain in limiting mag. confirmed (close loop & whole AO error), but also in the bright-end (lower aliasing!), from end-to-end simulations (for FLAO@LBT).

Wavefront sensors - 7

Pyramid vs. Shack-Hartmann, 2nd round

- Poyneer & Macintosh, 2004: spatial filtering of the SH WFS (lower aliasing error)
- Nicolle et al., 2004: optimized calculus of the SH signals (lower measurement error)
- Fusco et al., 2005: spatial filtering+optimized calculus => SH at the level of the Pyramid (and less uncertainties on stability and robustness...)
- Vérinaud et al., 2005 (in the framework of XAO and the ELT): Pyramid better close to optical axis, SH 'à la Fusco' better far from it.

Wavefront sensors - 8

Pyramid vs. Shack-Hartmann, 2nd round

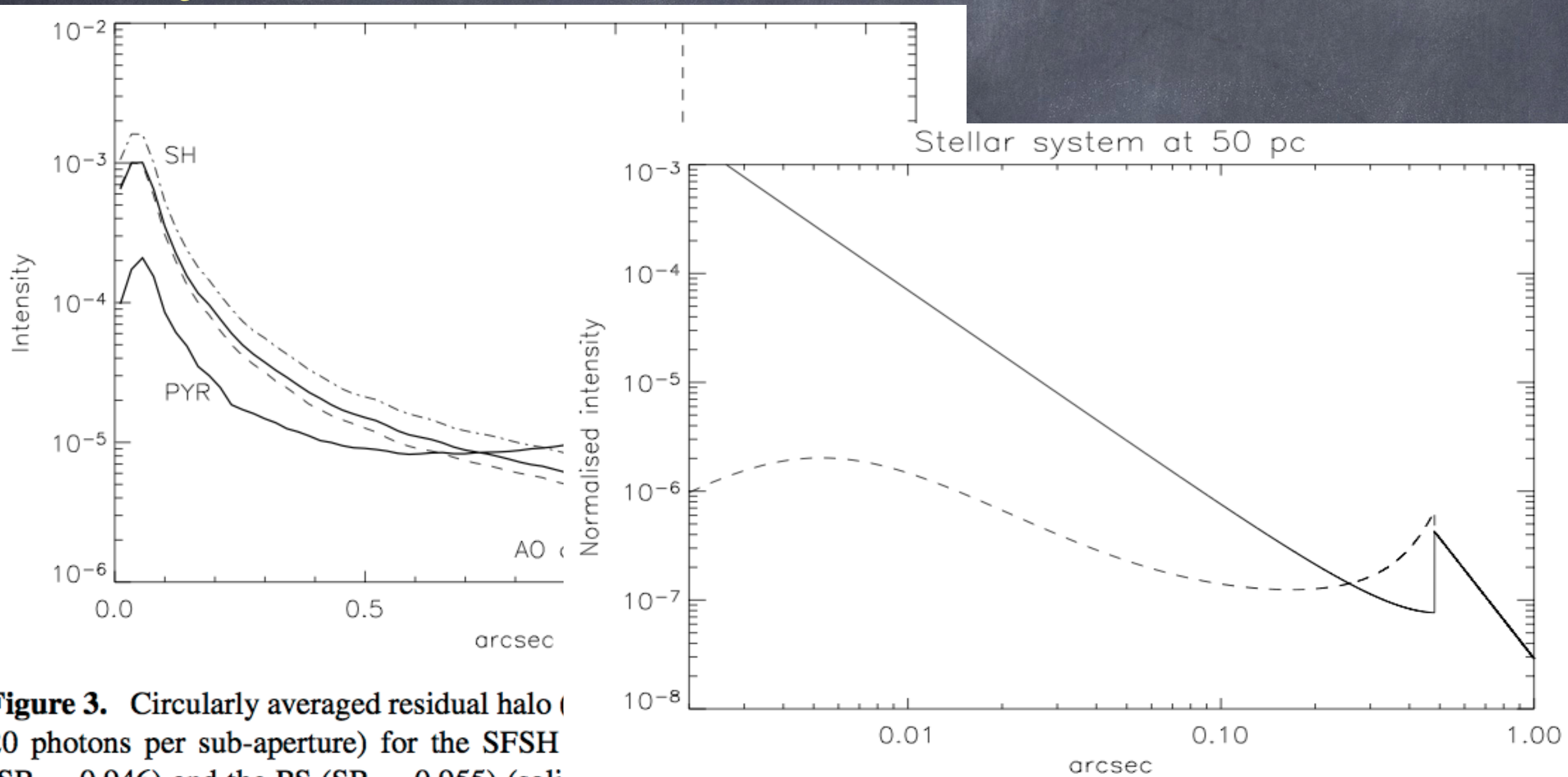


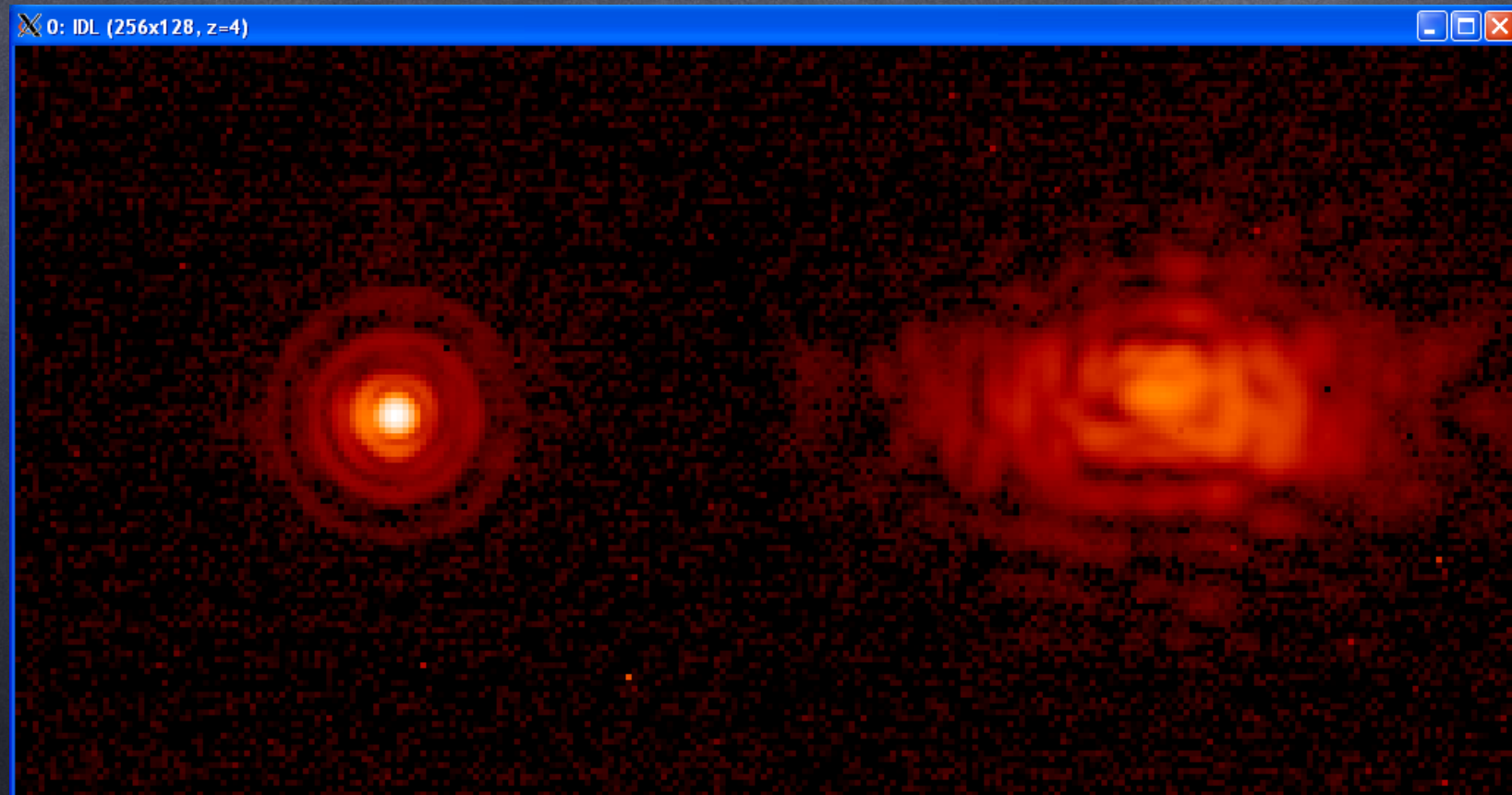
Figure 3. Circularly averaged residual halo (20 photons per sub-aperture) for the SFSH (SR = 0.946) and the PS (SR = 0.955) (solid line), the WCOG, 20 photons per sub-aperture (dotted line), and the PS, 20 photons per sub-aperture (dashed line).

Figure 7. Residual halo in the R band for a SFSH-based system (solid line, SR = 0.79) and a PS-based system (dashed line, SR = 0.81) with a 15-cm actuator pitch on a 100-m telescope. The guide star V magnitude is 8.2, seeing = 0.7 arcsec, $\tau_0 = 3$ ms, frame rate = 4 kHz.

Wavefront sensors - 9

Pyramid vs. Shack-Hartmann, 3rd & 4th rounds

- 2010: first images of FLAO@LBT on sky
- 2014: first images of SAXO/SPHERE@VLT in lab



Deformable correctors - 1

- Different technologies for correctors:
 - piezo-stacked arrays
 - piezo-electric bimorph mirrors
 - MEMS
 - voice-coil adaptive secondary mirrors (ASM)
 - multi-actuator adaptive lens (MAL) (!)
- Different coefficients for the fitting error, different strokes, different possible bandwidths, different possible number of modes, possible hysteresis, etc.

Deformable correctors - 2

146mm clear aperture



349 actuators on 7 mm spacing

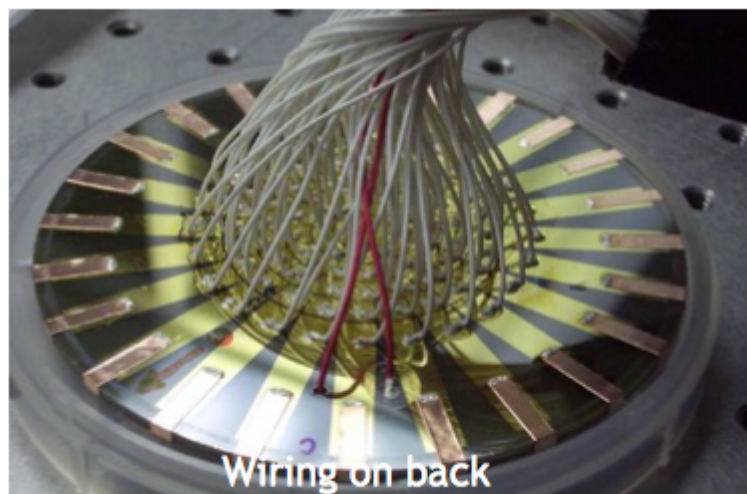
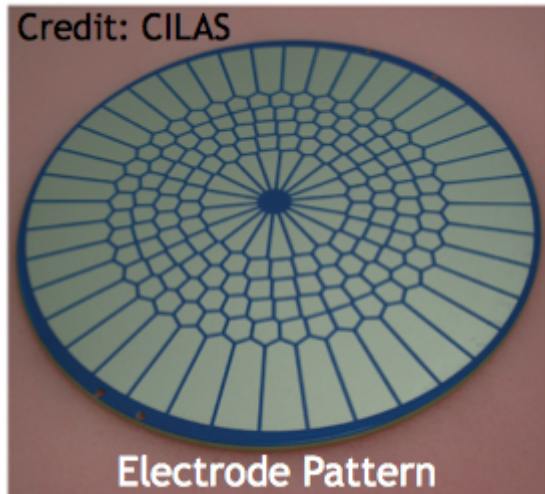


Kinetics @ Keck

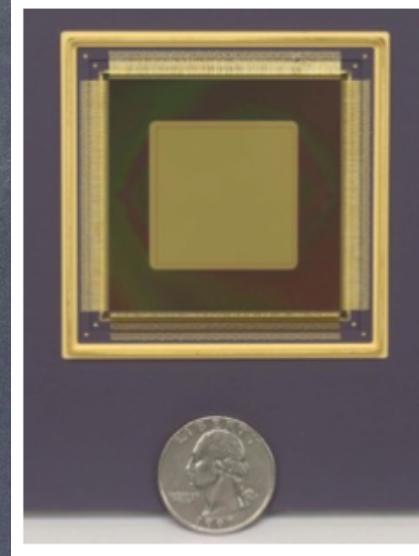
Piezo-stacked array

Bimorph

Credit: CILAS

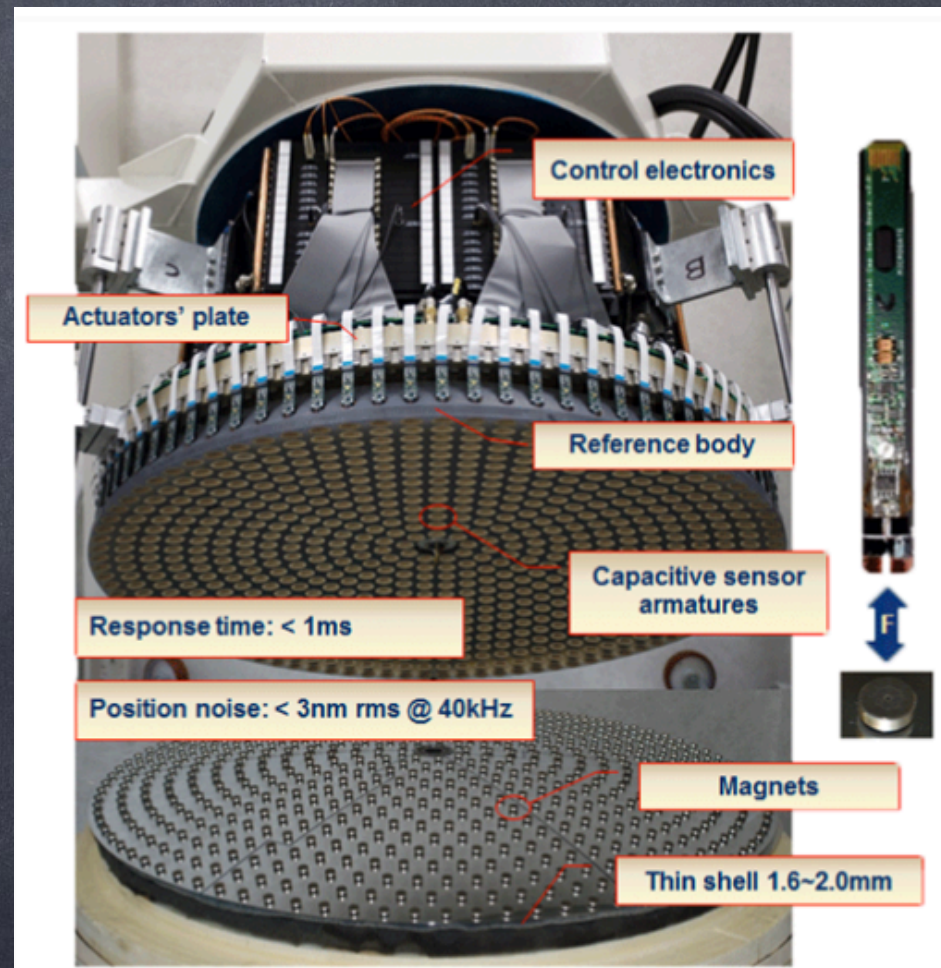


@Boston MC



MEMS

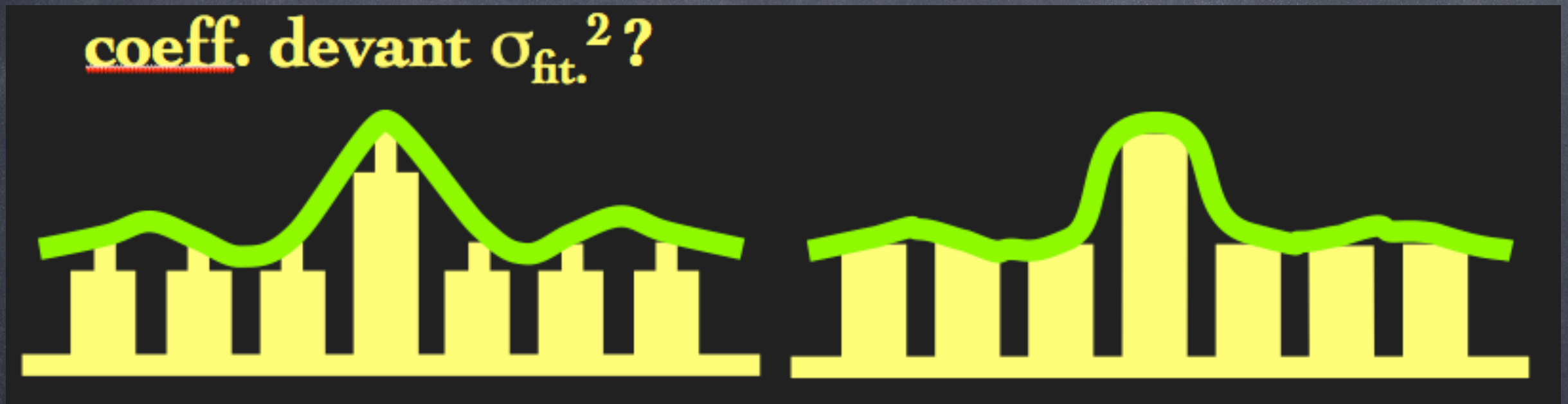
Voice-coil
(`adaptive secondary`)



(c) Micro gate

Deformable correctors - 3

- Different coefficients for the fitting error:



- Is the stroke enough ?
If not: necessity to add a tip-tilt mirror...

Deformable correctors - 4

- How many actuators for a given Strehl ratio ?
(considering a coeff. 0.3 for the fitting error)

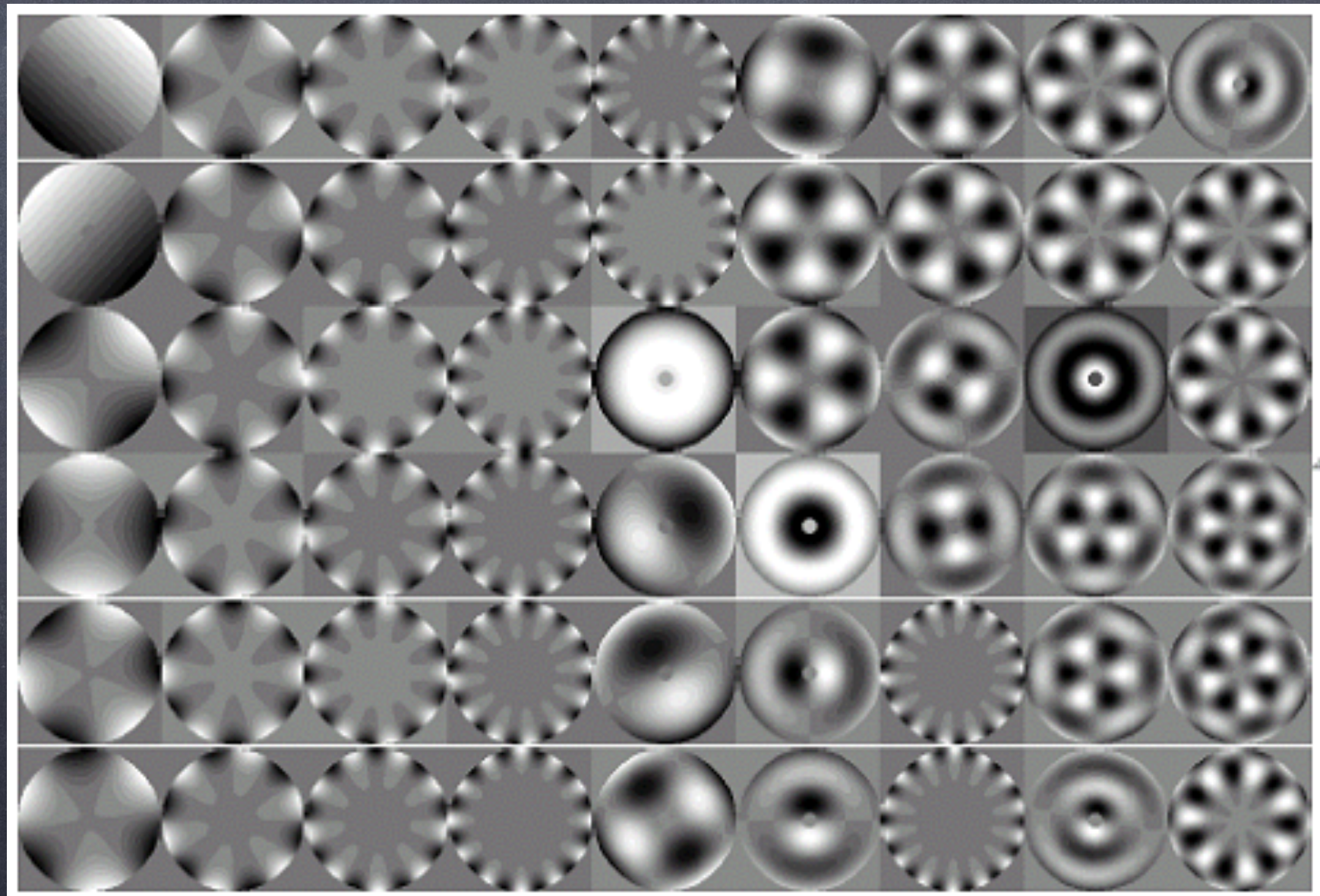
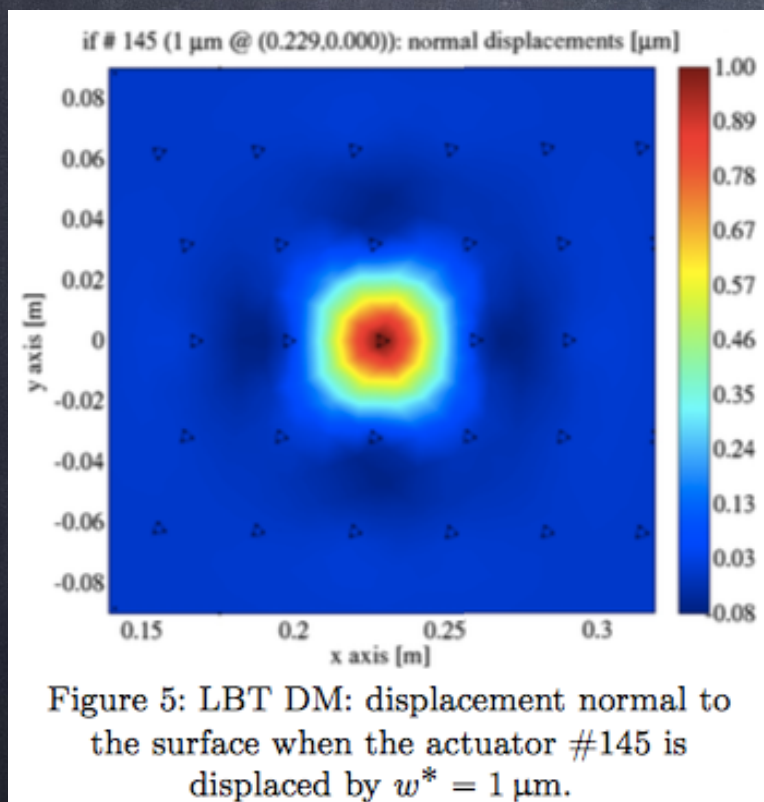
$$\sigma_{\text{fit.}}^2 = 0.3 \left(\frac{d_{\text{act.}}}{r_0} \right)^{\frac{5}{3}}$$

$$S_{\text{max}} = \exp(-\sigma_{\text{fit.}}^2)$$

- if $d = r_0$, then: $S_{\text{max}} = \exp(-0.3) \approx 0.74$
if $d = r_0/2$, then: $S_{\text{max}} = \exp(-0.3/2^{5/3}) \approx 0.91$

Deformable correctors - 5

- Influence functions $\rightarrow$ mirror modes



Deformable correctors - 6

- An interesting case: the Adaptive Secondary Mirror (ASM) technology developed for LBT [Brusa et al. 2003]

